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## **Tunable MEMS Cantilever Resonators**

### **Electrothermally Actuated and Piezoelectrically Sensed**

Boris Sviličić<sup>a,b,\*</sup>, Enrico Mastropaolo<sup>a</sup>, Rui Zhang<sup>a</sup>, Rebecca Cheung<sup>a</sup>

<sup>a</sup>Scottish Microelectronics Centre, University of Edinburgh, EH9 3JF, United Kingdom

<sup>b</sup>Faculty of Maritime Studies, University of Rijeka, Studentska ulica 2, 51000, Croatia

\*Corresponding author. Tel.: +385 99 211 6639. Email: svilicic@pfri.hr

#### **Abstract**

This paper reports on microelectromechanical (MEMS) cantilever resonant devices that are actuated electrothermally and sensed piezoelectrically, and have voltage tunable resonant frequencies. The devices have been designed as a two-port vertical-mode cantilever resonator. The single-clamped beam (cantilever) resonators have been fabricated in silicon carbide with top platinum electrothermal actuator (input port) and lead zirconium titanate piezoelectric sensor (output port). The performance of the devices has been demonstrated with two-port measurements of the transmission frequency response in atmospheric conditions. The measurements have shown that the devices with a beam length of 200  $\mu\text{m}$  and 250  $\mu\text{m}$  resonate in the frequency range 373 kHz – 523 kHz with Q factor in air up to 455. By applying DC bias voltage between 6 V and 11 V, a frequency tuning range of about 1,300 ppm has been achieved, with the tuning range being wider for the shorter cantilever. Simulated results for different cantilever lengths show that higher temperature and stress are induced in the shorter cantilever, indicating that the resonant frequency change observed as a function of tuning DC voltage is dominated by the stress effect rather than geometric effect.

**Keywords:** MEMS resonator, cantilever resonator, piezoelectric sensing, electrothermal actuation, tuning

## 1 INTRODUCTION

Micro-electro-mechanical systems (MEMS) resonators have been extensively researched as potential emerging technology for implementation in a variety of devices such as sensors, frequency references and filters [1-3]. Design of the resonant structure is a very important factor in MEMS resonators performance. Simplicity of the single-clamped beam (cantilever) structures and the fact that they can be fabricated relatively easily are the main motivation for their use in MEMS applications. In addition, even though cantilever resonators exhibit lower resonant frequency than double-clamped beam and circular membrane resonators, they possess the highest vibration amplitudes, which is very important for achieving good electrical sensing of the mechanical vibration.

Piezoelectric transduction has been used extensively for electrical sensing of MEMS resonators operation [4]. Main advantage of piezoelectric transduction is the ability to generate electrical potential actively in response to an applied mechanical stress, and thus can be used for sensing with no need for an external bias voltage source, as required in piezoresistive and capacitive transductions. In addition, it offers stronger electromechanical coupling, better impedance matching and relatively simpler fabrication compared to electrostatic transduction [5]. On the other hand, electrothermal actuation, among conventional techniques for electrical induction of mechanical vibrations, offers advantages such as simple fabrication process, low actuation voltages, impedance matching and effective resonant frequency tuning [6-11]. The ability to tune resonant frequency actively is of paramount importance for maintaining performance of MEMS resonators, as MEMS fabrication process uncertainties (dimensional and material property variations, and residual stresses) and changeable environmental conditions can cause shift in the resonant frequency [12].

Recently, we have demonstrated the combination of electrothermal actuation and piezoelectric sensing on double-clamped beam MEMS resonators [11,13]. Although cantilever structures have been driven into resonance electrothermally successfully, the resonant operation has been detected optically [14], capacitively [15] and piezoresistively [16]. This paper reports on design, fabrication, simulation and testing of two-port cantilever MEMS resonators with electrothermal actuation and piezoelectric sensing. The devices have been designed as vertical-mode resonator with electrothermal actuator (input port) and piezoelectric sensor (output port) placed on top of the single-clamped beam. The electrothermal actuator and piezoelectric sensor have been positioned to achieve effective actuation and sensing respectively. By performing two-port measurements of the devices transmission frequency response in atmospheric conditions, resonant behaviour has been studied. The origin of resonant frequency change in the devices has been investigated by comparing experimental and simulation results.

## **2 DEVICE DESIGN AND OPERATION PRINCIPLES**

The devices have been designed as a two-port single-clamped beam resonator (Figure 1). Electrothermal actuator (input port) and piezoelectric sensor (output port) are placed on the top of single-clamped beam, thus operating as a vertical-mode resonant device. For the structural material, cubic silicon carbide (3C-SiC) has been used due to its excellent mechanical properties that allow SiC resonators to achieve higher resonant frequencies compared to equivalent silicon (Si) resonators [17]. In addition, high thermal conductivity makes it particularly suitable for electrothermal actuation. Platinum (Pt) thin layer has been used as the electrothermal actuation electrode, forming a bilayer structure. Electrothermal actuation of bilayer structures relies on the fact that the coefficient of thermal expansion varies for different materials. When applying a

voltage difference across the actuation electrode, the induced electrical current generates Joule heating thus resulting in thermal expansion and mechanical strain. The bilayer structure of materials with different thermal expansion coefficients (Pt and 3C-SiC) allows enhanced mechanical strain of the structure [18]. As the dissipated power depends on the squared value of actuation voltage, a device can be driven into resonance if the frequency  $f_{AC}$  of an actuating voltage containing an AC component that is equal to half of the structure's natural frequency  $f_0$  ( $f_{AC}=f_0/2$ ) [14]. However, a device can be driven into resonance using the actuation frequency equal to the structure's natural frequency ( $f_{AC}=f_0$ ), so far as actuation signal contains both AC and DC component.

A schematic of the device design is shown in Figure 2. The input electrothermal (ET) electrode has been designed as a plain plate (slab layout) with the length of 20  $\mu\text{m}$  and width of 30  $\mu\text{m}$ . The strong electromechanical coupling offered by electrothermal transduction allows induction of relatively large vibration amplitude by positioning actuation electrode close to the root of the beam [19]. In addition to the simple layout of the electrothermal actuator, the design allows us to place an additional port for the piezoelectric sensor on the remaining part of the single beam. As the piezoelectric material, a lead-zirconium-titanate (PZT) has been used due to its high piezoelectric coefficient in order to enhance the electromechanical coupling in the sensing part of devices [5]. PZT layer has been sandwiched between two Pt layers, forming the piezoelectric sensor that is placed on the top of the 3C-SiC beam. When the device is electrothermally driven into the resonance, the beam's vertical vibration can be sensed by detecting an oscillating voltage with a frequency equal to the frequency of the mechanical oscillations across the piezoelectric material (output port). In order to achieve a high electrical output, the piezoelectric sensor was positioned close to the anchor, where the electrothermal

actuation is maximum. However, the distance of 13  $\mu\text{m}$  between the input and output electrodes was kept to minimize electrical crosstalk between the two ports.

### 3 EXPERIMENTAL DETAILS

The main steps of the fabrication process flow are illustrated in Figure 3. The process begins with a 2  $\mu\text{m}$  thick 3C-SiC epilayer grown on 4 inch Si wafer, followed by the deposition of a 100 nm thick silicon dioxide ( $\text{SiO}_2$ ) passivation layer and a 10 nm thick titanium (Ti) adhesion layer. Next, the Pt/PZT/Pt stack has been deposited with thicknesses of 100/500/100 nm respectively. After deposition of the all layers, the photolithographically defined ports have been patterned by dry etching of the top and bottom Pt layers and wet etching of the PZT layer. For patterning the beam geometry, a 3  $\mu\text{m}$  thick  $\text{SiO}_2$  masking layer has been deposited, the beam shape has been defined photolithographically and the exposed  $\text{SiO}_2$  has been dry etched. The 3C-SiC beam has been etched in inductively coupled plasma with a  $\text{SF}_6/\text{O}_2$  gas mixture [20]. Finally, the 3C-SiC beam has been released with  $\text{XeF}_2$  chemical etching. The fabrication process details for the Pt/PZT/Pt/3C-SiC structures can be found elsewhere [21]. Devices have been fabricated with the beam length of 200 and 250  $\mu\text{m}$ , and the beam width of 100  $\mu\text{m}$ .

Electrical characterization of the devices has been performed using an HP 8753C vector network analyzer and signal-ground radio-frequency probes. The network analyzer has been calibrated using the two-port short-open-load-through (SOLT) calibration method. The devices under test have been directly connected to the network analyzer without the need for any signal amplification or impedance matching. In order to perform electrothermal actuation and resonant frequency tuning, the input AC signal provided with the network analyzer has been superimposed to a DC voltage provided by an additional stabilized DC source. The output signal

has been taken from the top metal contact of the piezoelectric sensor, while the bottom metal contact has been grounded. The devices were measured in air, at room temperature and atmospheric pressure.

In order to study the origin of resonant frequency change in electrothermally actuated and tuned cantilever resonators, the devices have been simulated using finite element method (FEM) software, ANSYS. The influence of applied tuning DC voltage on the temperature and stress in the 3C-SiC layer has been investigated.

#### **4 RESULTS AND DISCUSSION**

Two-port measurement of the transmission frequency response, both magnitude and phase, of a device with the beam length of 200  $\mu\text{m}$  is shown in Figure 4. The device has been electrothermally actuated using an input AC signal power of 10 dBm and DC bias voltage of 9 V. A resonant peak has been measured at 522.2 kHz with a quality (Q) factor of 415 in air. Tuning of the resonant frequency has been performed electrothermally by varying the input DC bias voltage. Figure 5 shows the measured resonant frequency shift of the device actuated with constant input AC signal power of 10 dBm, while the tuning DC voltage has been swept in the range of 6 V – 11 V with step of 1 V. With the tuning DC voltage increase from 6 V to 11 V, the resonant frequency decreases from 522.6 kHz to 521.9 kHz (a shift of about -1,300 ppm). It is believed that the detected change in resonant frequency is due to surface stress-induced change in the stiffness of cantilever [22,23]. Figure 6 shows the stress and temperature in 3C-SiC layer as a function of the tuning DC voltage, extracted at the position of 25  $\mu\text{m}$  from the anchor for cantilevers with beam lengths of 200 and 250  $\mu\text{m}$ . As can be seen in Figure 6, the increase of tuning DC voltage induces an increase of temperature in general which enhances the thermal

expansion of the materials forming the structure, resulting in an increase of the induced stress and consequently in a decrease of the resonant frequency.

The Q factor has been found to be affected by the change of the tuning DC voltage. Figure 5 shows the Q factor as a function of the applied tuning DC voltage. The Q factor has been extracted from the transmission magnitude plots by calculating the ratio of the resonant frequency and the frequency bandwidth of 3 dB transmission magnitude drop. In the presence of tuning, the device exhibits relatively high values of the Q factor in air (345 - 455), indicating the ability to operate in a non-vacuum environment. The obtained Q factors in air are comparable to that of similar cantilever resonators covered with piezoelectric thin films [24-26]. Q factor represents a measure of the stored energy in relation to the dissipated energy of a system in one cycle of vibration [22]. The generated heat induced by DC tuning voltage increase most probably affects the balance of the ratio, resulting in the observed Q factor increase. From Figure 7, it can be noted that even for the highest input power, the transmission magnitude curve is not distorted, which indicates good linearity and power handling capacity. It is worth mentioning that testing of the vertical mode resonator performed under vacuum conditions should give significantly higher values for the Q factor, as the energy loss effect of air damping would be reduced [22]. In addition, reduction of the piezoelectric sensor area covering the cantilever's surface along the beam length direction from the tip could also increase the Q factor [13,26].

Figure 8 shows the measured frequency tuning characteristic of the device with the beam length of 250  $\mu\text{m}$  together with the frequency tuning characteristic of the 200  $\mu\text{m}$  device previously given in the Figure 5. Both devices are of the same design and differ in the beam length only. The devices have been taken from the same die (fabrication related differences have been minimized) and tested under the same operating conditions. The 250  $\mu\text{m}$  device, in the



presence of the tuning, resonates in the frequency range from 373.2 kHz to 373 kHz (frequency tuning range of about -600 ppm). From Figure 8, a larger shift in the resonant frequency that progressively increases with the tuning DC voltage increase is observed for the device with shorter beam. From simulations, Figure 6, it can be seen that higher temperature is induced in the device with shorter beam length, resulting in larger stress induced and consequently larger frequency shift. The above experimental and theoretical observations confirm that, with the beam length and width much greater than the beam thickness (thin structure), the resonant frequency shift of our devices is dominated by stress effect instead of geometric effect [23]. The observed frequency tuning capability in our cantilevers is similar to other electrothermal cantilever resonators [19,28,29]. However, the frequency tuning capability of the cantilevers is significantly smaller compared to our previous finding with the electrothermally actuated double-clamped beam [11,13] and ring resonators [30], indicating that the cantilever resonators are much less sensitive to surface stress-induced variations in resonant frequency [23]. The frequency tuning characteristic can be improved either by scaling dimensions of the resonant structure or by optimizing the layout of the electrothermal actuator to cover more surface area of the beam. Nevertheless, the obtained tunability can be used for adjusting a sensor or filter to work on a specific frequency or to compensate for frequency shifts arising from changes in the operating conditions or from fabrication process imperfections.

## **5 CONCLUSIONS**

The design, fabrication, simulation and operation of tunable MEMS cantilever resonators actuated electrothermally and sensed piezoelectrically have been reported. The devices have been designed as vertical-mode resonator with Pt electrothermal actuator and PZT piezoelectric

sensor placed on top of the 3C-SiC single-clamped beam. The position of the actuator and sensor has been optimized to achieve effective actuation and sensing. Resonant frequency tuning is demonstrated by applying DC bias voltages in the range of 6 V – 11 V and a tuning range of about -1.300 ppm has been achieved, with a wider tuning range measured for the shorter cantilever. A larger temperature and stress induced in the shorter cantilever has been observed in the simulations. The frequency shift observed as a function of DC bias voltage has been attributed to the surface stress-induced change in the stiffness of cantilever. It has been shown, by comparing experimental and simulation results for devices with different beam lengths, that the resonant frequency change is dominated by the stress effect rather than the geometric effect. The presented MEMS resonant devices show relatively high resonant frequencies with high Q factor in air, which makes them a very interesting candidate for use in a variety of sensing and filtering applications that require frequency tuning.

## **ACKNOWLEDGMENTS**

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## Figure Captions

Figure 1. SEM image of one of the fabricated MEMS cantilever resonator with the electrothermal actuator (input port) and piezoelectric sensor (output port) placed on the top of single-clamped beam.

Figure 2. Schematic of the designed device with the beam dimensions.

Figure 3. Fabrication process flow of electrothermally actuated and piezoelectrically sensed 3C-SiC cantilever resonators.

Figure 4. Two-port measurement of the transmission frequency response, both magnitude and phase, for the electrothermally actuated device using the input AC signal power of 10 dBm and DC bias voltage of 9 V.

Figure 5. Measured resonant frequency shift and Q factor in air of the device with the beam length of 200  $\mu\text{m}$  versus tuning DC voltage.

Figure 6. Simulated temperature and stress in 3C-SiC layer versus tuning DC voltage.

Figure 7. Transmission magnitude plots of the device with the beam length of 200  $\mu\text{m}$  for different tuning DC voltages.

Figure 8. Measured resonant frequency shift versus tuning DC voltage with the beam length  $L_b$  as a parameter.

## Figures

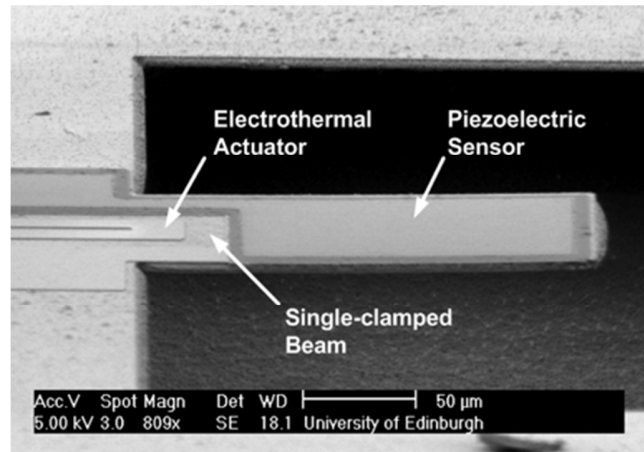


Figure 1

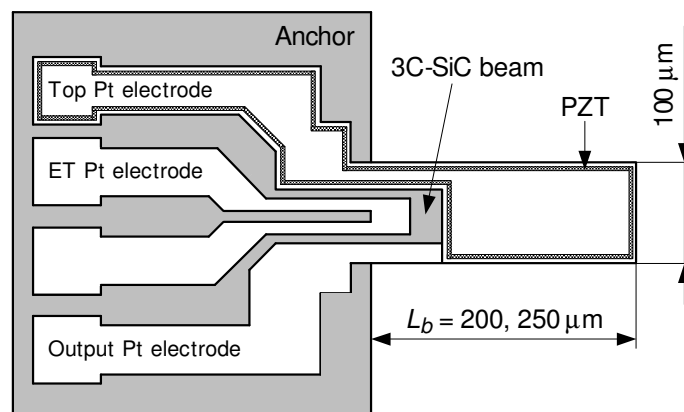


Figure 2



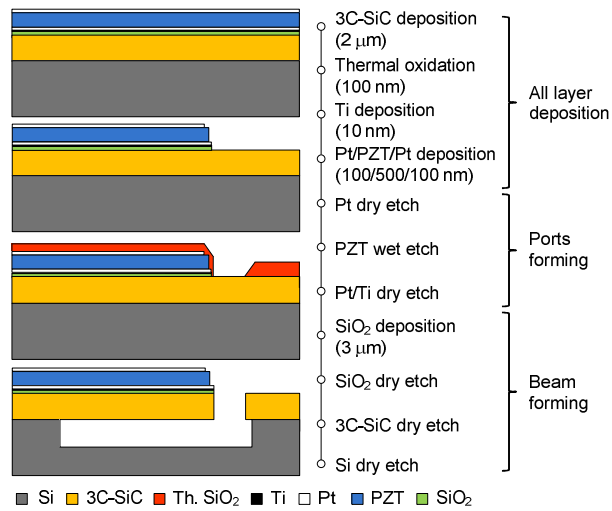


Figure 3

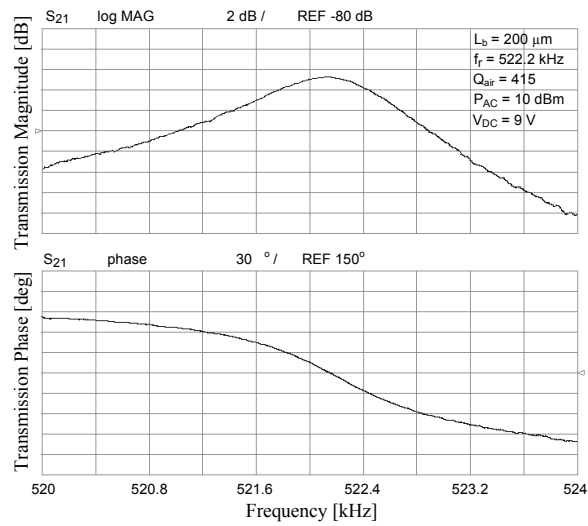


Figure 4

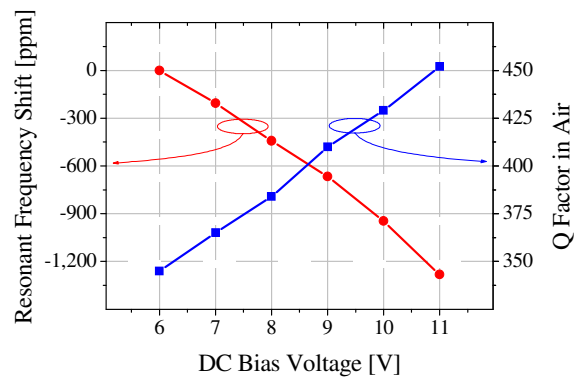


Figure 5

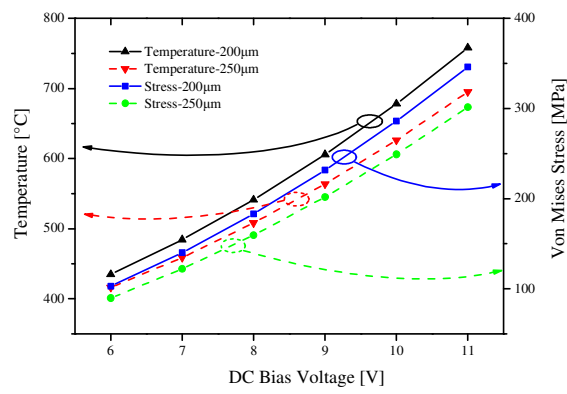


Figure 6

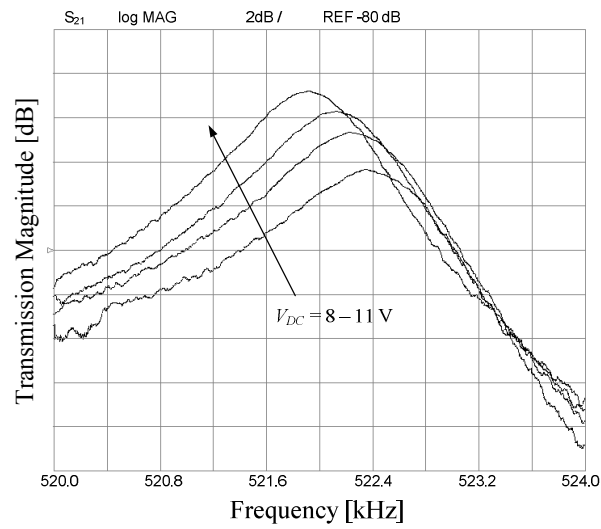


Figure 7

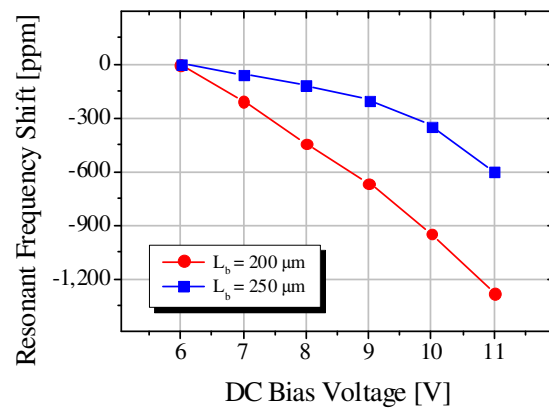


Figure 8